General Circulation Modeling of Extrasolar Planets

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Outline

- Background
- Model
- Large-scale features
- Some important numerical aspects
- Subgrid-scale phenomena and instability
- Summary

Background

- There are currently over 400 extrasolar planets known.
  - Many of them are very close-in (less than 0.1 AU).
  - Close-in, “hot planets” are expected to have permanent day/night sides, due to tidal synchronization

- *What is the atmospheric flow and temperature distribution under such a heating condition?*

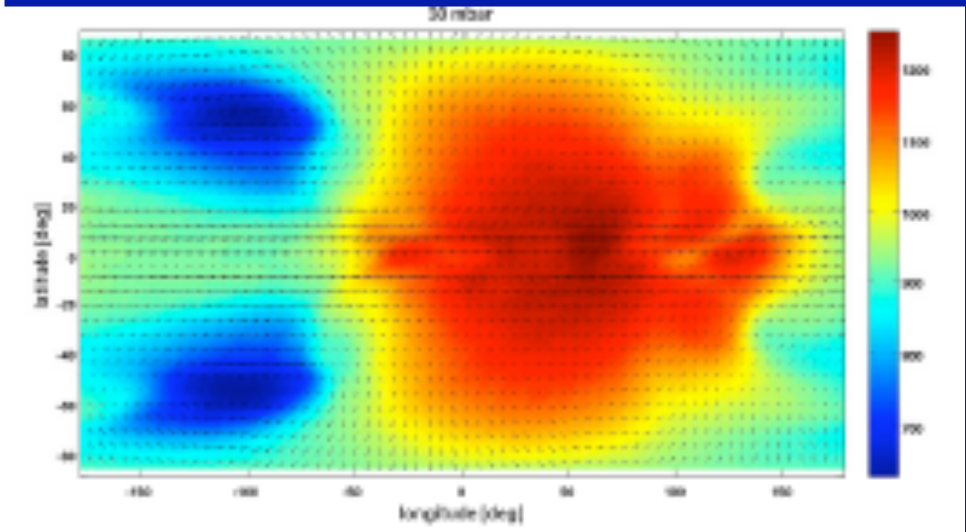
- We use a state-of-the-art, 3-D general circulation model (GCM) to perform series of numerical simulations

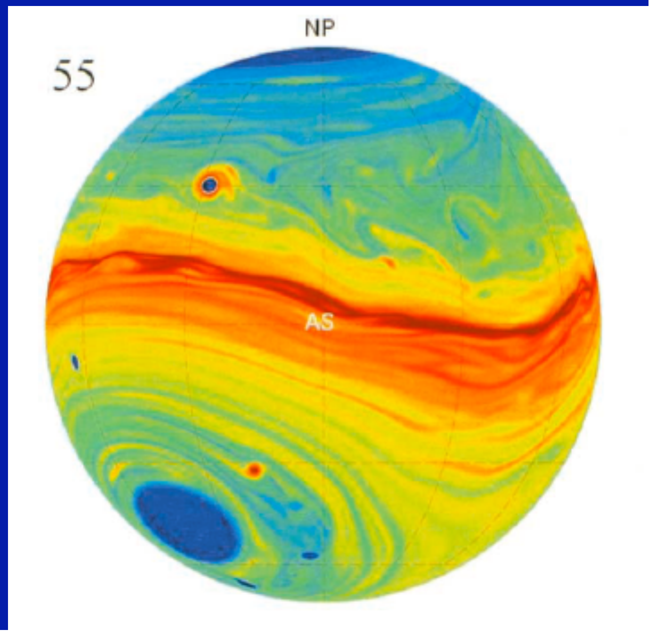
Hot-Jupiters: Observations

- Transits and radial velocity measurements
  - transmission spectra, secondary eclipse, orbital phase curves
- Constraints on size, mass, orbit, composition, *temperature*
- Need 3D distribution of temperature and radiatively active species to interpret spectra
- Global circulation models are needed to interpret current observations and guide future observations

Large-scale Circulation Modeling

- 3D Navier-Stokes equations (Dobbs-Dixon & Lin)
- 3D Primitive equations -- GCM (Cooper & Showman, Showman et al., Menou & Rauscher, *Thrastarson & Cho*)
- Equivalent-Barotropic and Shallow-Water equations (*Cho et al.*, Langton & Laughlin)
- “Pure” 2D equations (Langton & Laughlin)





3-D General Circulation Model

- NCAR Community Atmosphere Model (CAM) <-- "state-of-the-art" GCM
- Solves the hydrostatic primitive equations on a rotating sphere
- Pseudospectral method <-- highly accurate AND well-tested

$$
\begin{aligned}
\frac{\mathrm{D}\mathbf{v}}{\mathrm{D}t} + \left(\frac{u}{R_p}\tan\phi\right)\mathbf{k}\times\mathbf{v} &= -\nabla_p\Phi - f\mathbf{k}\times\mathbf{v} + \mathcal{D}_v \\
\frac{\partial\Phi}{\partial p} &= -\frac{1}{\rho} \\
\frac{\partial\omega}{\partial p} &= -\nabla_p\cdot\mathbf{v} \\
c_p\frac{\mathrm{D}T}{\mathrm{D}t} &= \frac{\omega}{\rho} + \dot{Q} + \mathcal{D}_T \\
p &= \rho R T
\end{aligned}
$$

Hot-Jupiter Simulations

- Temperature dragged to "equilibrium" profile, T_e, on a time scale τ
- Idealized representation of stellar heating

$$\dot{Q} = -\frac{1}{\tau}(T - T_e)$$

$$T_e = T_m + \Delta T_e cos(\phi) cos(\lambda)$$

- Input planetary parameters from observations
  – HD209458b: 84 h period, 1.3 Jupiter radii
- Domain from ~ 10^{-3} -100 bar
- Resolution T42 (128x64) and T85 (256x128) with 26 levels

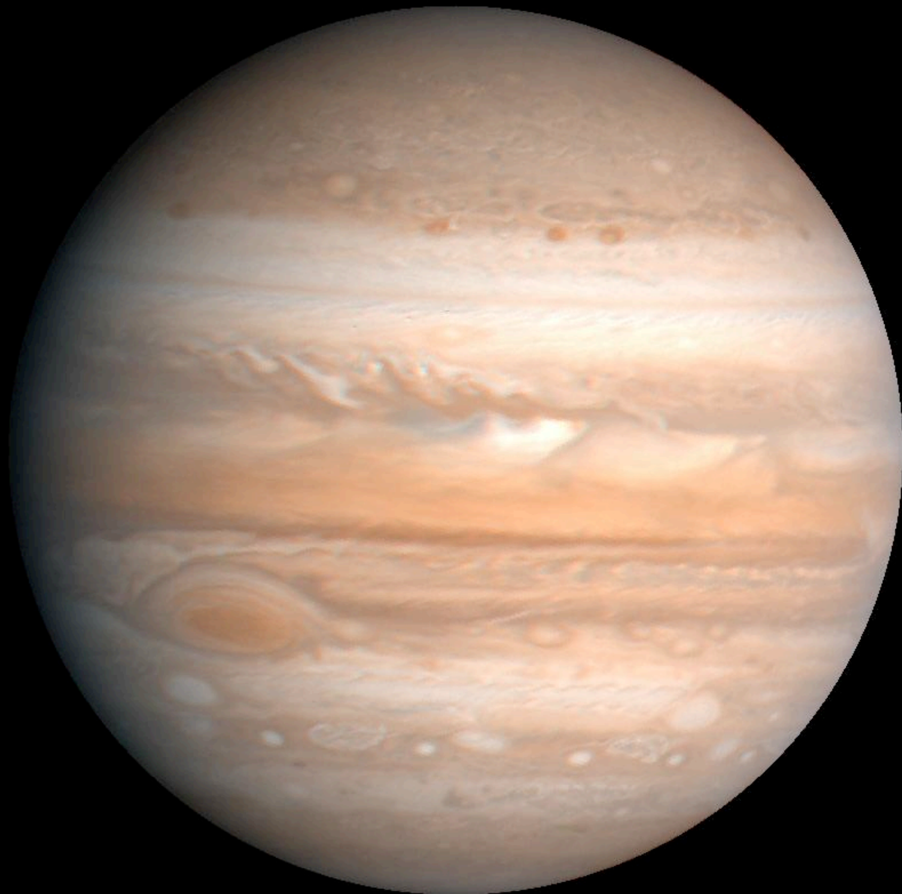
Relevant Scales - Regime

- Rotation rate moderate, but Coriolis force still important (Rossby number ~ 1)
- Buoyancy frequency N ~ 10^{-3} s^{-1} => T ~ 1 hour
- Pressure scale height H ~ 500 km
- Deformation radius (NH/f) ~ planet radius
- Rhines scale ($\pi(2U/\beta)^{1/2}$) ~ planet radius
- Strong, asymmetric heating *and* cooling (i.e., *net* heating)

Comparison With What We Know

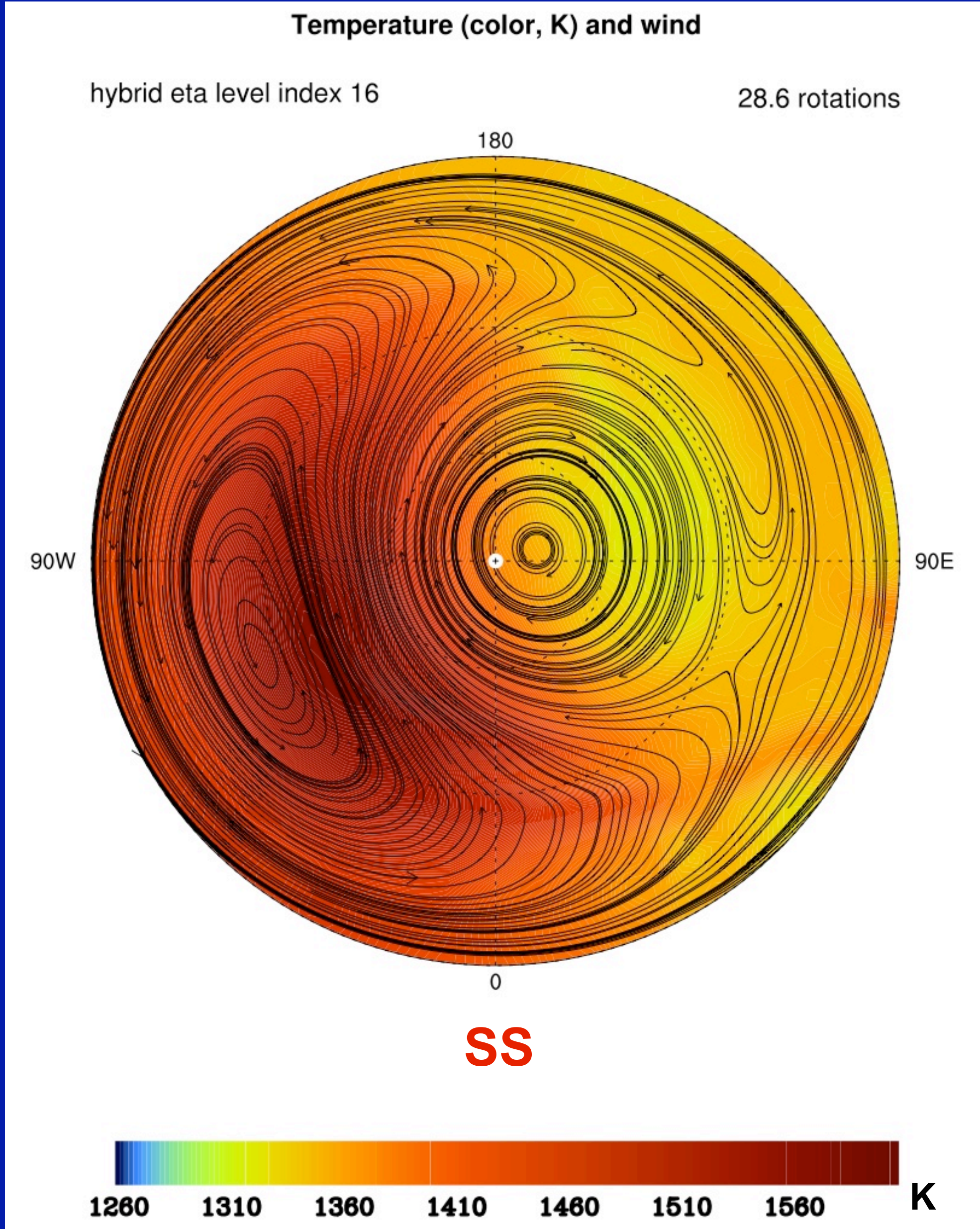
Earth

Jupiter



Robust Features in Our Simulations

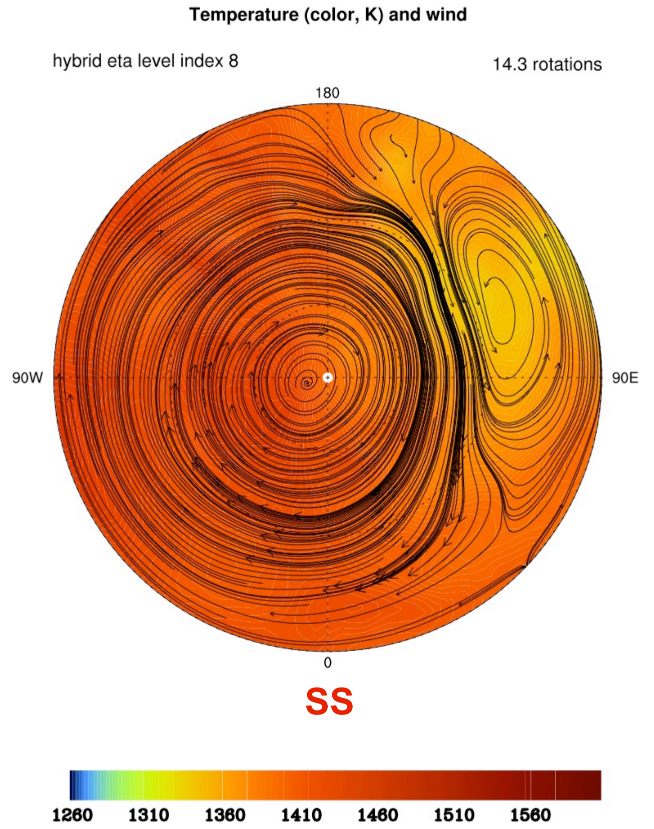
- Low number of jets (~3)
- Large scale vortices
- Relatively homogenized temperature
  - Forcing with ~1000K day-night difference
  - Get only a few hundred K difference max, localized
- Time variability



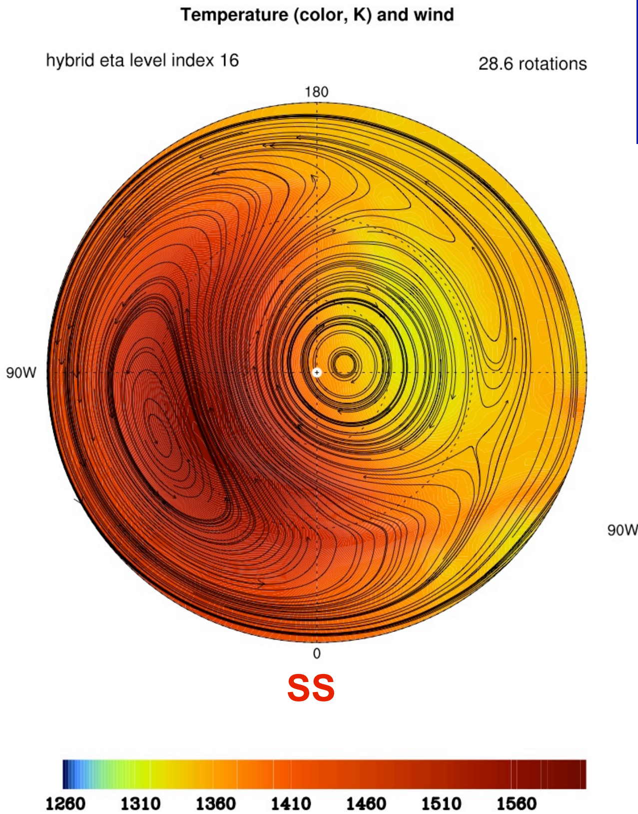
Temperature - Vertical Structure

p ~ 100mb

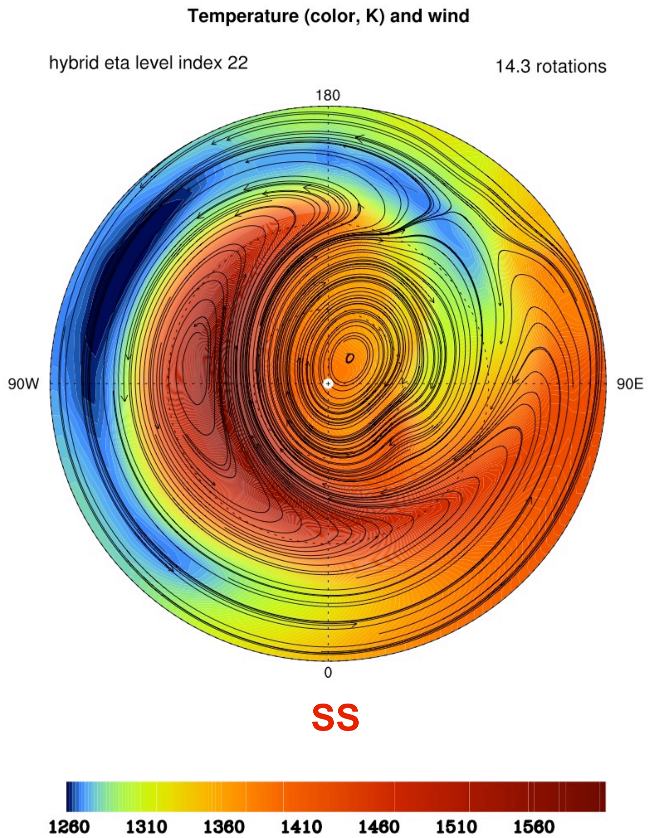
Far from simple hot day - cold night scenario



p ~ 400mb

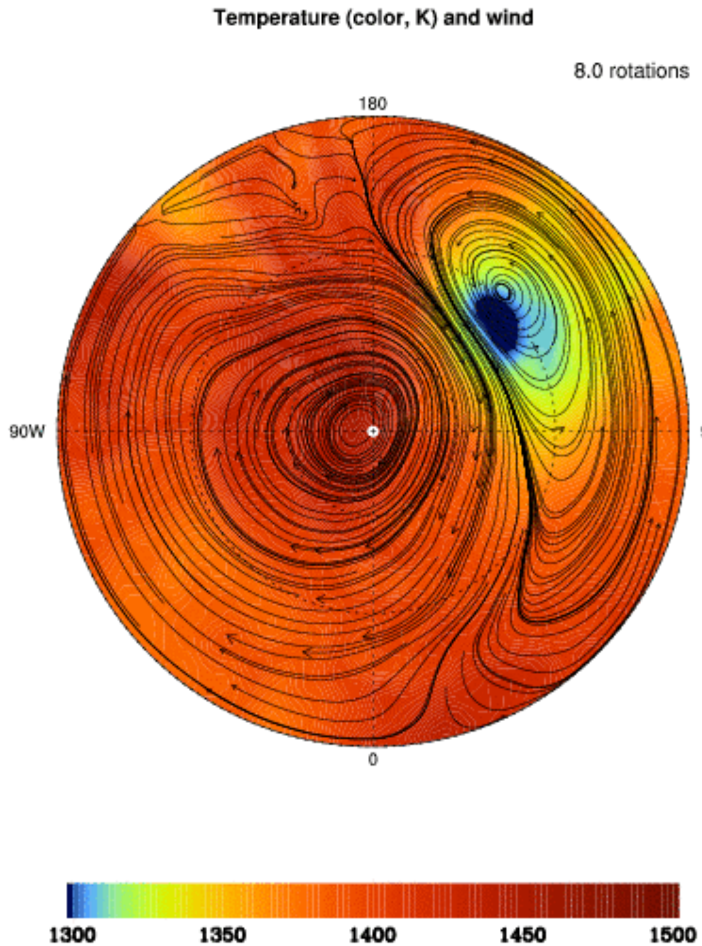


p ~ 900mb



Mix of barotropic and baroclinic

Storms - Time Variability



Extensive Sensitivity Study

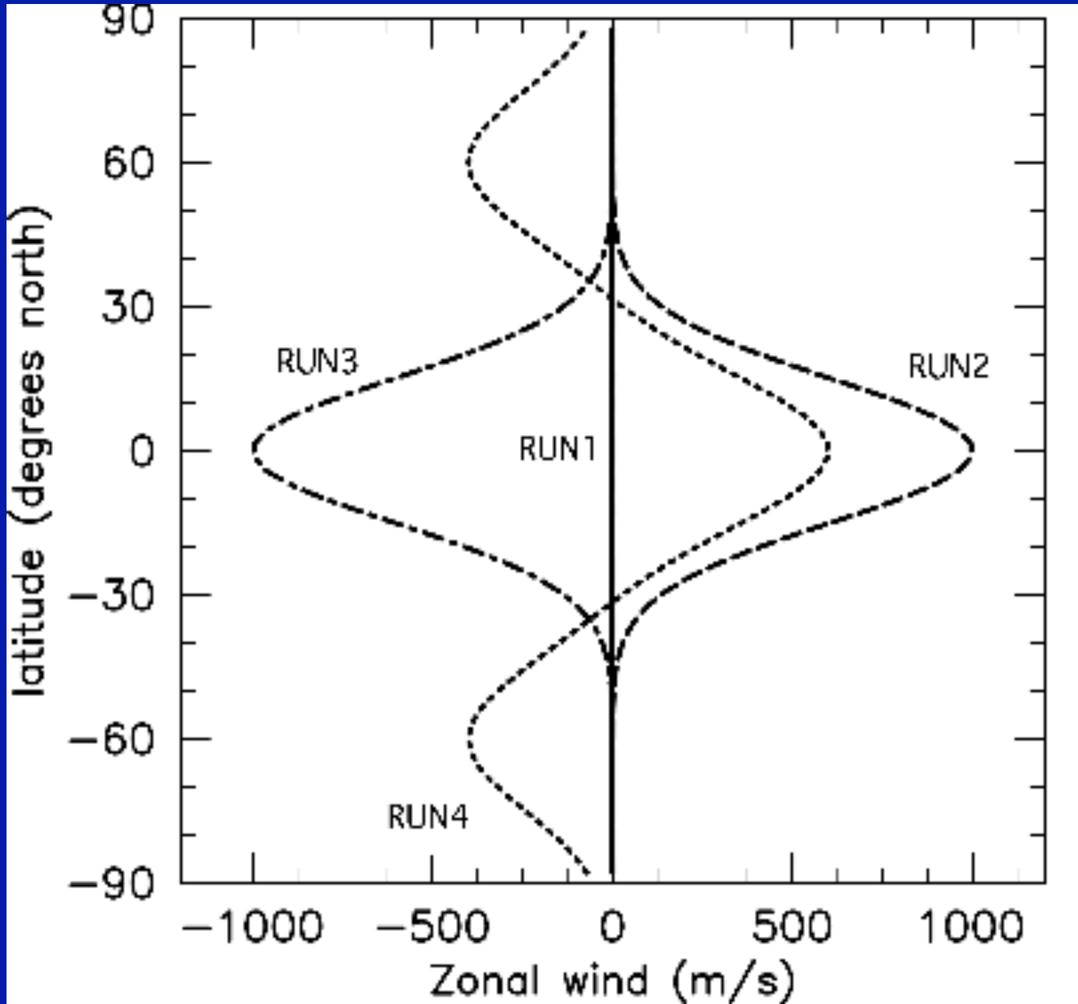
- Vary parameters individually
  - Numerical parameters

    (e.g. artificial viscosity)
  - Thermal forcing

    (equilibrium temperature profile, drag time scale)
  - Initial conditions

Varying Initial Conditions

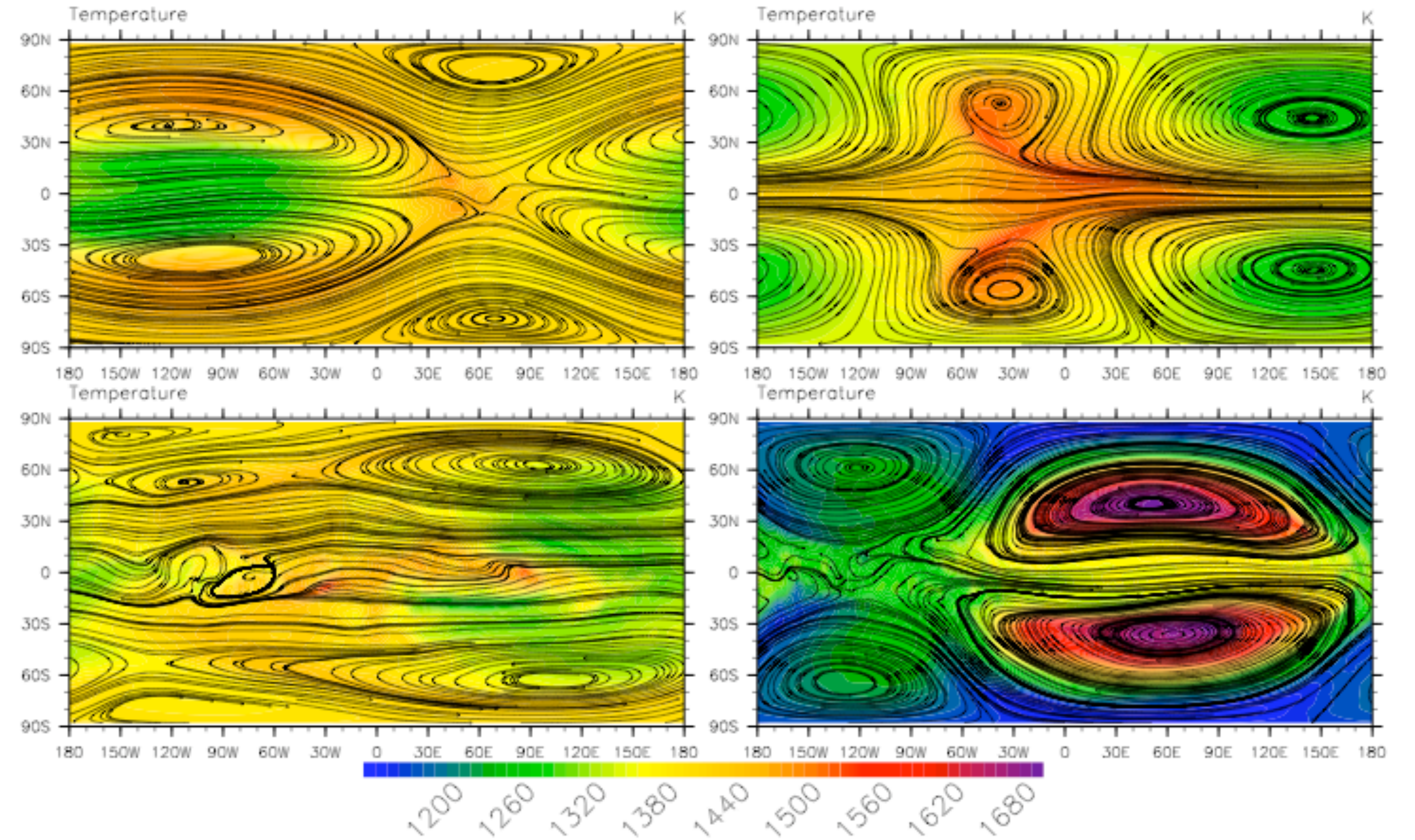
Thrastarson & Cho 2010



Dependence on Initial Conditions

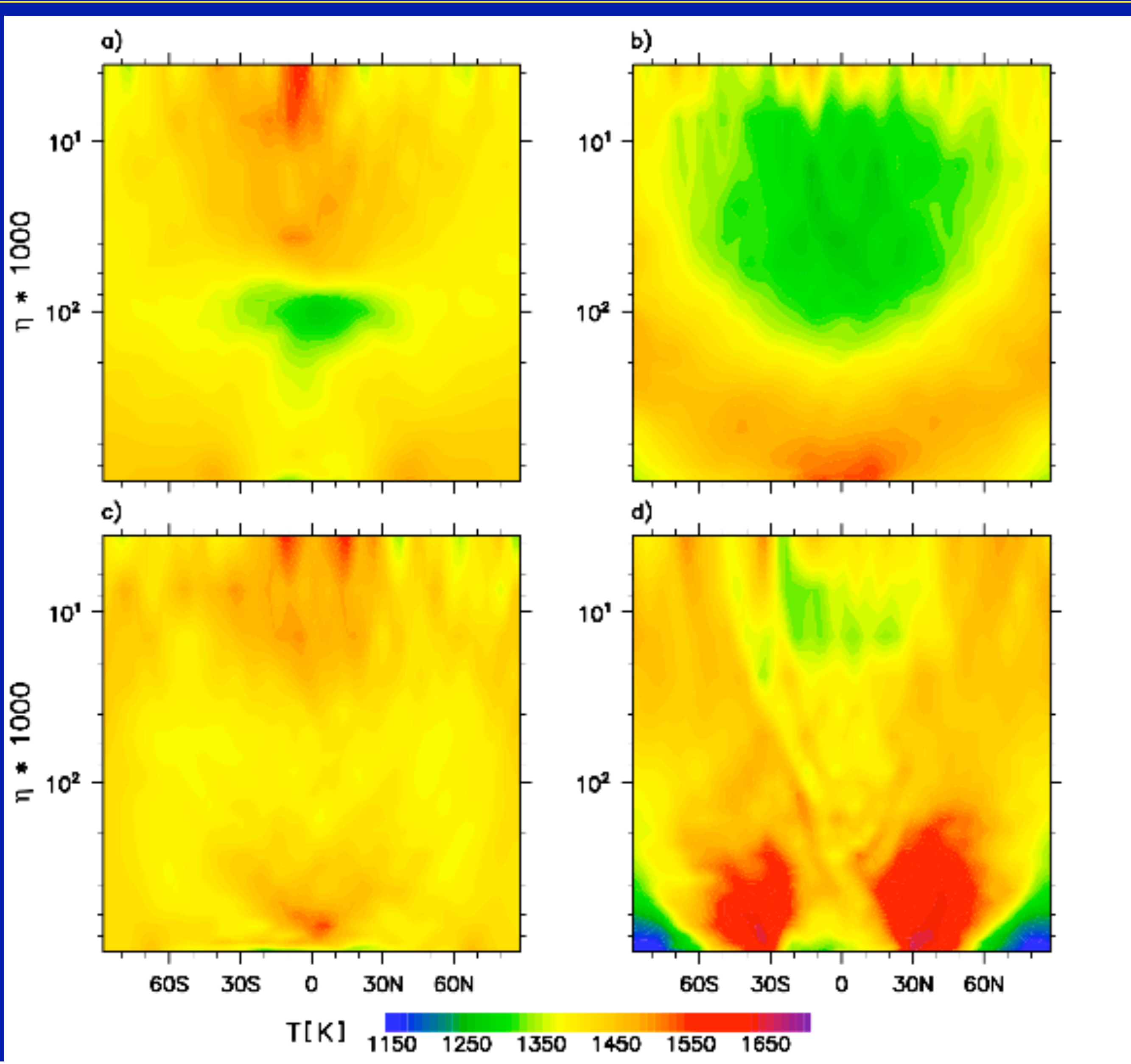
Simulations differing only in initial wind state

Thrastarson & Cho 2010



Location and sizes of vortices, and the associated temperature patterns, strongly depend on the initial wind configuration

Variety in Vertical Structure



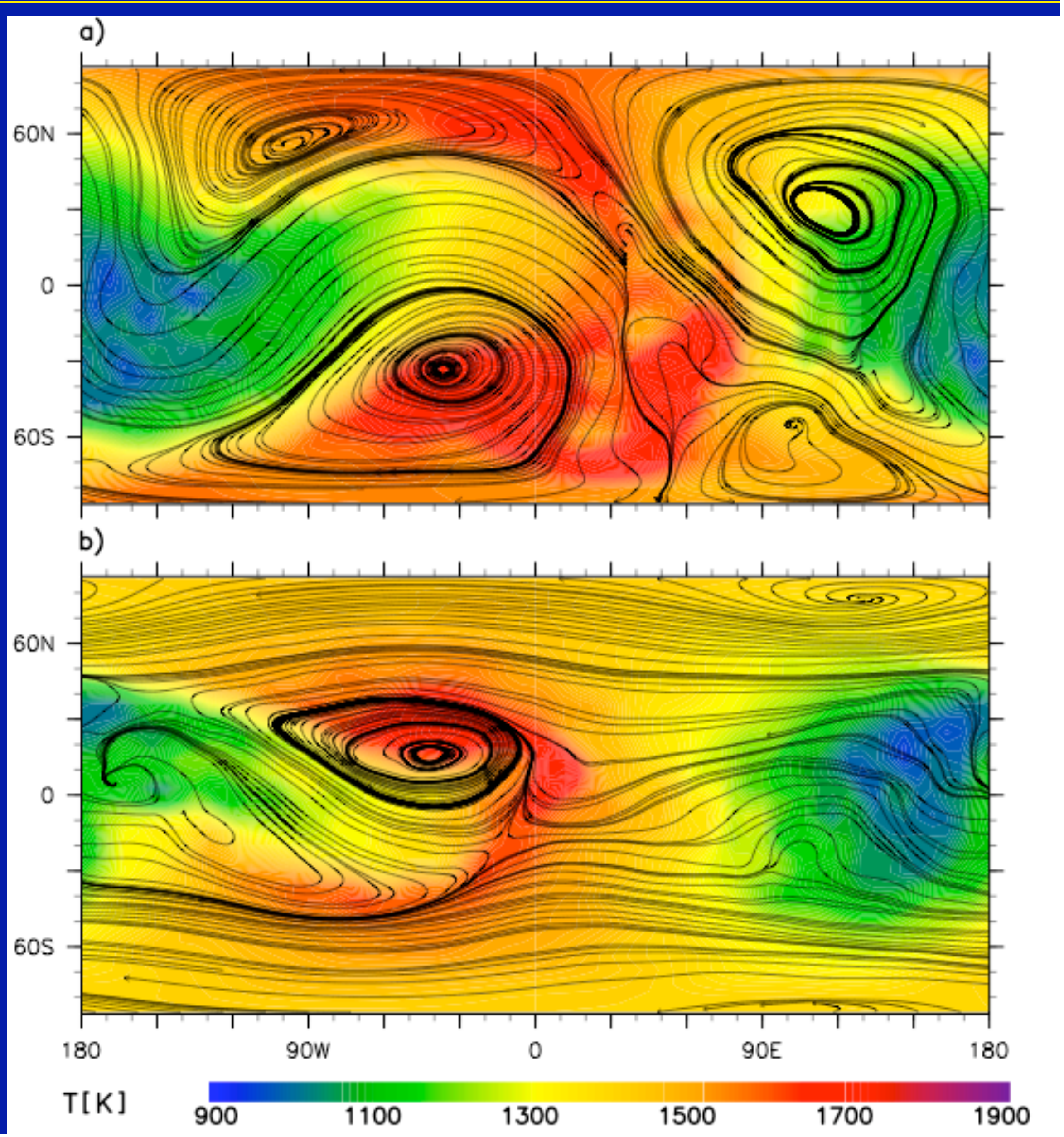
Short Thermal Drag Time

τ = 0.5 planet rotations

$$\dot{Q} = -\frac{1}{\tau}(T - T_e)$$

Initialized with small noise

Initialized with a westward equatorial jet

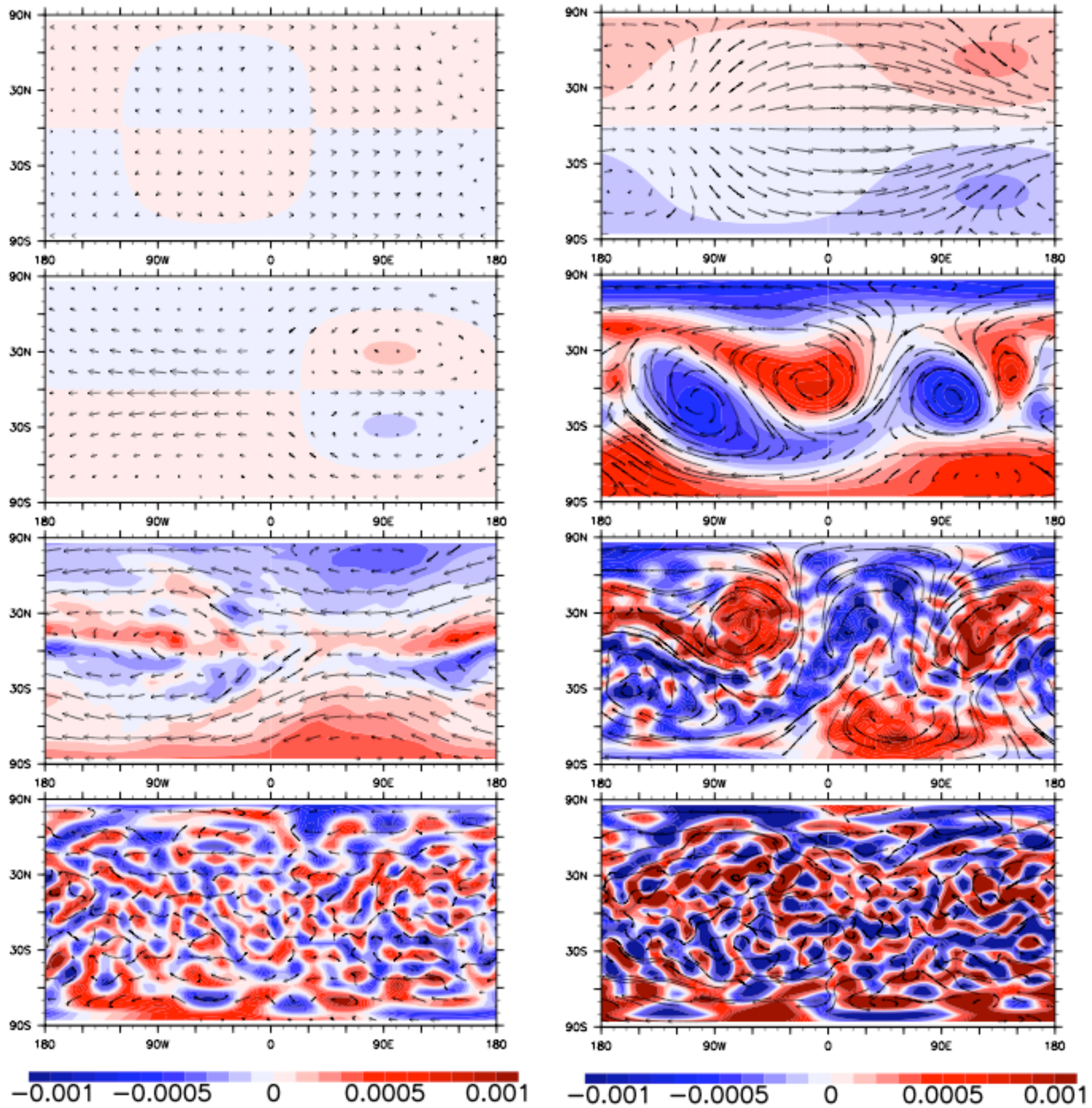


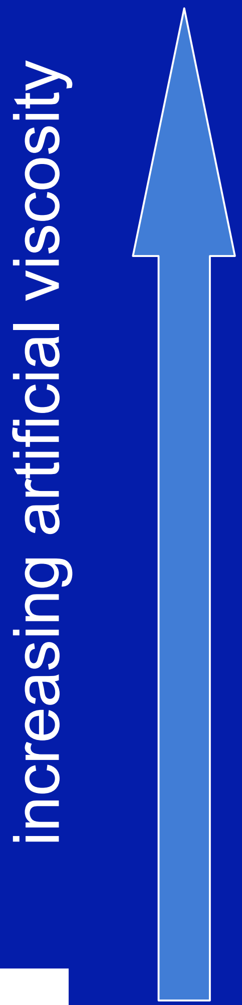
Thermal Drag Time and Dissipation

Vorticity maps

τ = 3 days

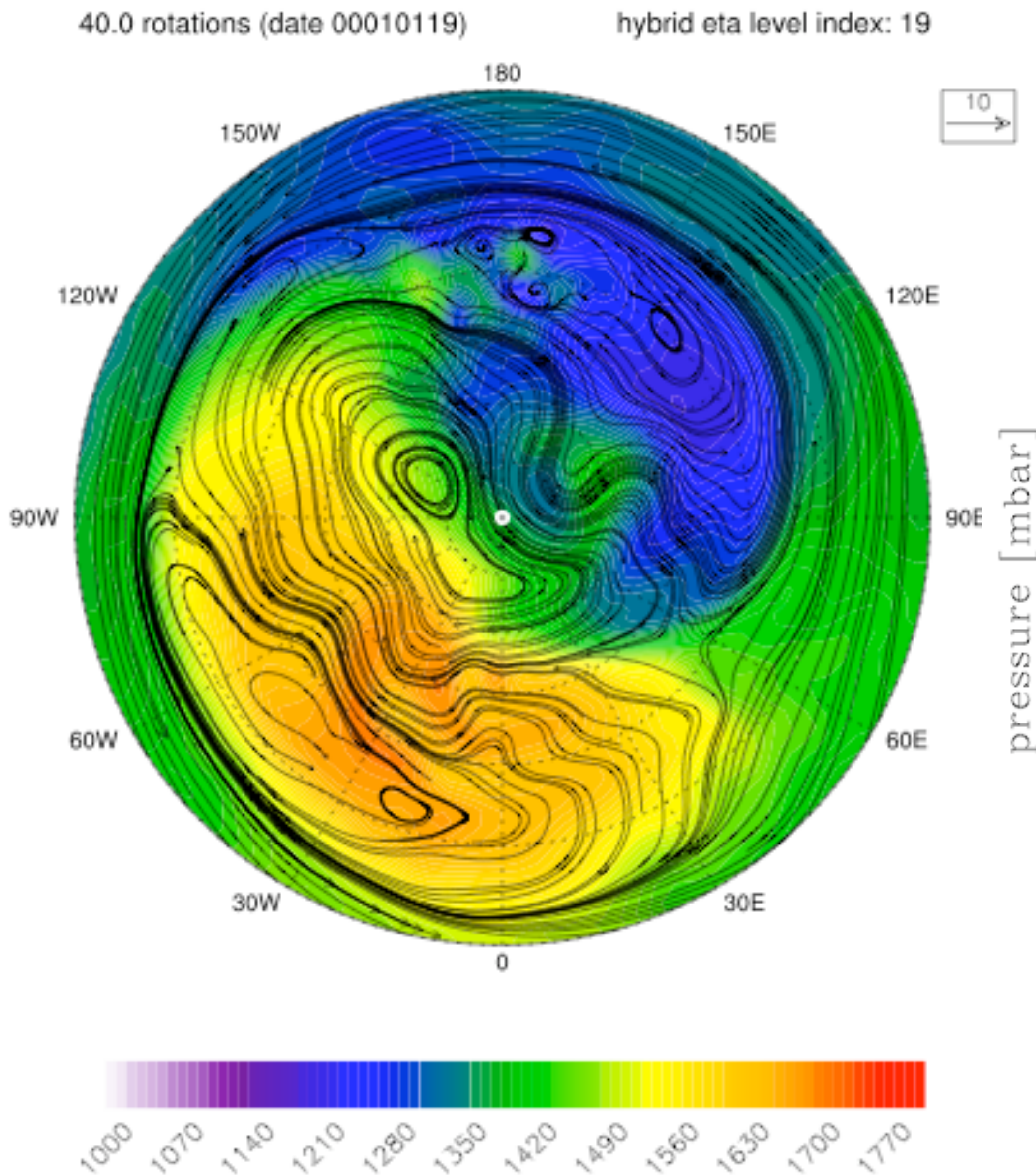
τ = 0.1 day



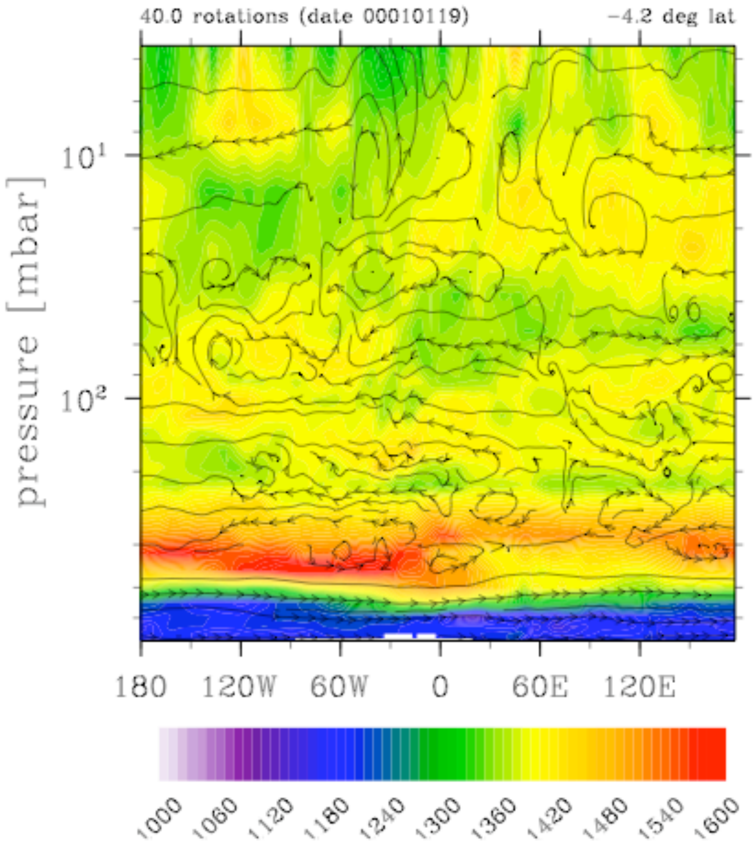


$$\dot{Q} = -\frac{1}{\tau}(T - T_e)$$

Thermal Forcing Variations



Forcing applied within a *thin* layer



Gravity Waves

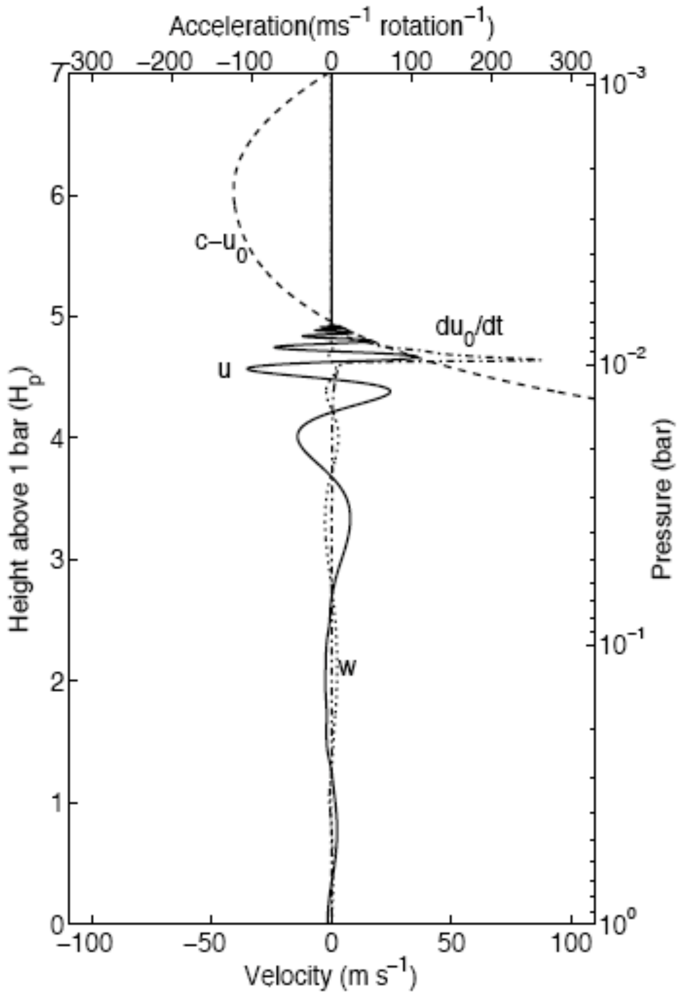
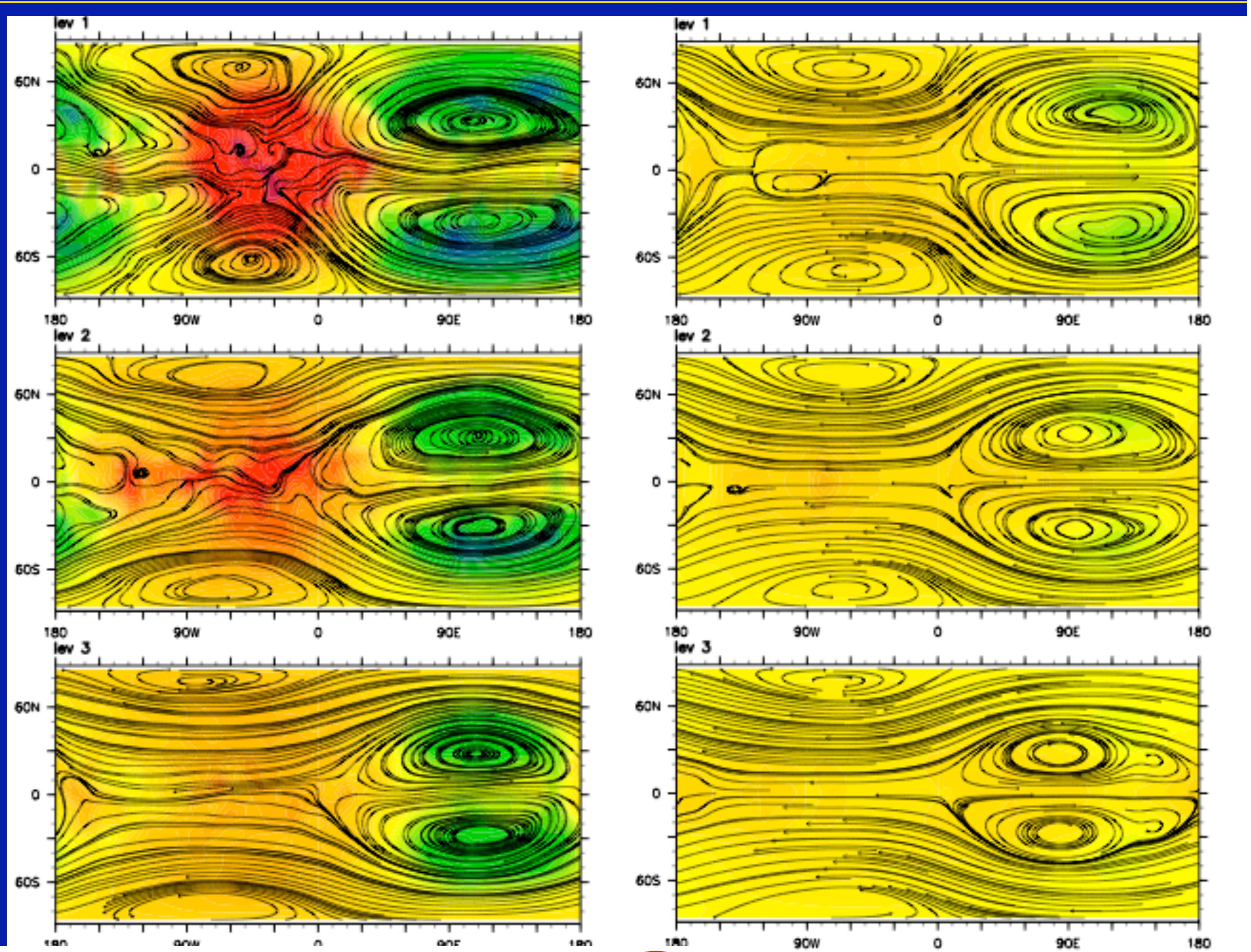


FIG. 4.— A gravity wave with $c = 600$ m s^{-1}, propagating in an atmosphere with profiles shown in Figure 3. The horizontal perturbation velocity u (—), intrinsic phase speed, $c - u_0$ (···), and the mean flow acceleration du_0/dt (−·−) are shown. The intrinsic phase speed becomes zero at $z/H_p \approx 5$ and the wave encounters a critical level. In the layers just below the critical level the wave saturates and sheds momentum into the mean flow, causing it to accelerate, peaking at a rate over 250 m s^{-1} rotation^{-1}.

- Watkins & Cho (2010)
- Gravity waves created by various sources and mechanisms
- Can have significant effects on the flow and temperature
- Limited resolution in global 3D models => parameterizations

Wind Drag

Rayleigh drag term added in the momentum equation, in the uppermost layers



$$\frac{D\mathbf{v}}{Dt} + \left(\frac{u}{R_p}\tan\phi\right)\mathbf{k}\times\mathbf{v} = -\nabla_p\Phi - f\mathbf{k}\times\mathbf{v} + \mathcal{D}_v - \frac{1}{\tau_v}\mathbf{v}$$

Baroclinic Instability

- Growth rate:

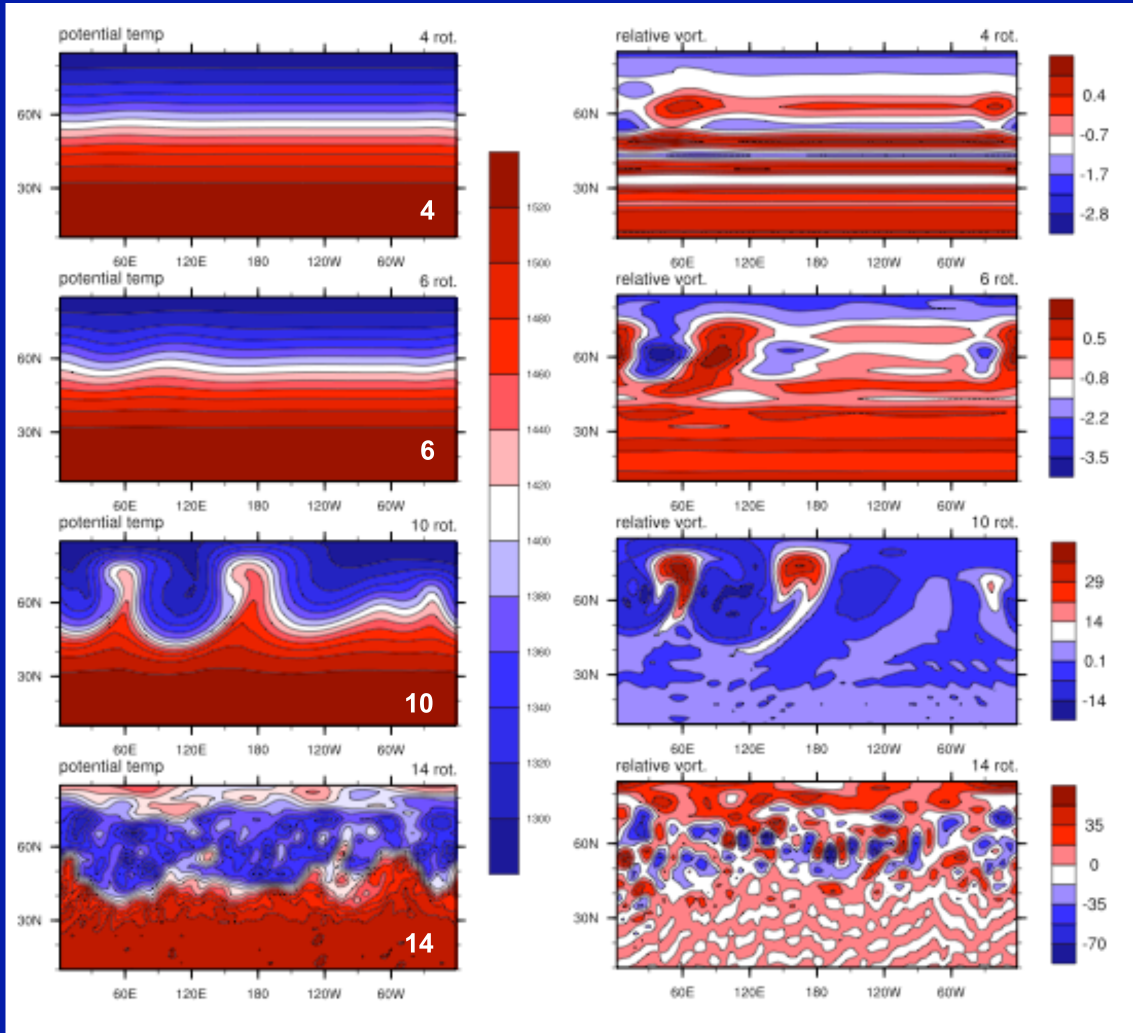
  ~5 planet rotations

- Gravest mode: ~2

- Turbulence after ~14

  HD209458b rotations

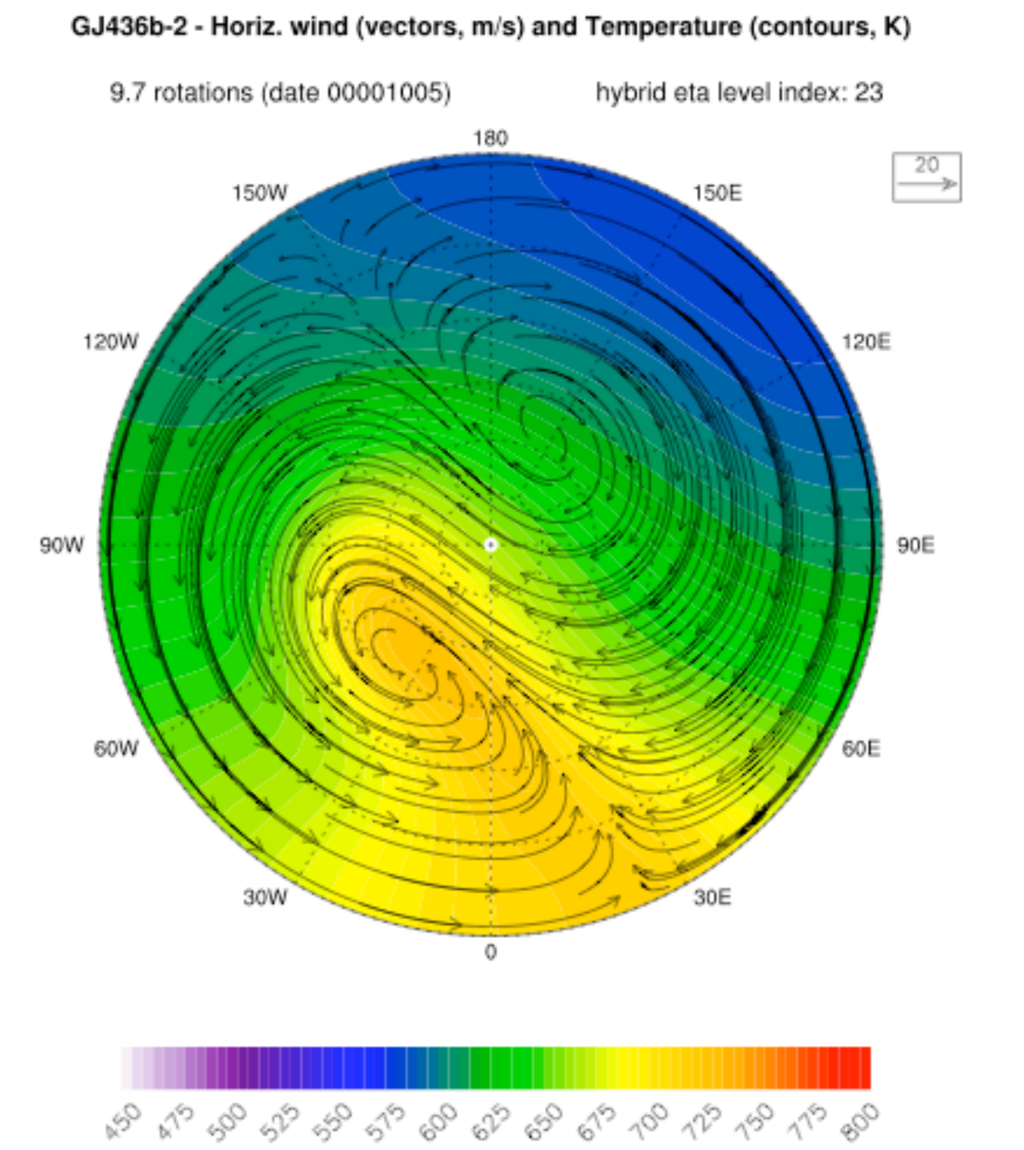
Potential temperature (K) Relative vorticity ($*10^{-6}\ m^2s^{-2}$)



Reference pressure layer (975 hPa) evolution of potential temperature and relative vorticity for eastward jet centered at 55N

Towards Hot Neptunes and Super Earths

- Smaller planets with a solid/ocean surface have been and will be observed
- Build on what we´ve learned about Hot Jupiters and their modeling, as well as Solar System planets
- GJ436b
  - 23 M_{Earth}
  - 63 h orbit
  - T_{eff} ~ 700 K)



Summary

- Hot Jupiter simulations - main results
  - low number of jets
  - large scale vortices
  - temperature homogenization,
    hot/cold spots away from sub/anti-stellar points
  - time variability
- Idealized models - not to be used for making “hard predictions”, but useful for gaining physical insights and studying mechanisms and flow regimes
- Limited observations - sensitivity studies essential

Future Work

- Closer look at waves and instabilities present
- Parameterizations and numerical treatment of sub-grid scale and ill-resolved phenomena
- Hot-Neptunes and Super-Earths
- Surface effects, clouds
- Clever ways of treating radiation